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DIVISION OF THE
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M. M. LEIGHTON, *Chief*
URBANA

REPORT OF INVESTIGATIONS—NO. 146

# APPLICATION OF MINERALOGY TO SOIL MECHANICS

## (1) SOME FUNDAMENTAL FACTORS INFLUENCING THE PROPERTIES OF SOIL MATERIALS

## (2) THE COMPOSITION IN RELATION TO THE PROPERTIES OF CERTAIN SOILS

BY

RALPH E. GRIM

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Topographic Mapping in Cooperation with the United States Geological Survey.

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# CONTENTS

# SOME FUNDAMENTAL FACTORS INFLUENCING THE PROPERTIES OF SOIL MATERIALS

BY

RALPH E. GRIM

THE IMPORTANT FACTORS of composition controlling the properties of soil materials may be classified as follows (Ref. 4*):

1) Clay-mineral composition—the relative abundance of the clay-mineral components and their particle-size distribution.
2) Nonclay-mineral composition — the relative abundance of each mineral and the size-grade distribution of its particles.
3) Electrolyte content—the amount and kind of exchangeable bases and any water-soluble salts.
4) Organic content—the amount and kind.
5) Miscellaneous textural characteristics such as shape of quartz grains, degree of parallel orientation of clay-mineral particles, and silicification.

Not all of these factors apply in any given soil material, and their relative importance is not always the same. Current researches in the writer's laboratory and elsewhere have shown that certain components which may be present in soil materials frequently exert a tremendous influence on properties, even though they are present in very small amounts. The addition or subtraction of such components by weathering processes, groundwater movement, or construction activities can therefore change greatly the properties of soil material.

This paper considers some of these components and offers an explanation of their action on the basis of present concepts of the structure of soil materials. It will serve our purpose best to start with a theory of the structure of soil materials in the plastic condition.

* References are given at end of paper, p. 11.

## THEORY OF THE STRUCTURE OF SOIL MATERIALS IN THE PLASTIC CONDITION

Water added to dry soil materials is adsorbed by the clay minerals and perhaps some other components. The important clay minerals are made up of flake-shaped units that occur both as unit flakes and as aggregates of book-like masses of flakes (Ref. 4). Much of the water is adsorbed on the basal plane surfaces of such units.

Hendricks and Jefferson (Ref. 7) have suggested that the water molecules have a definite orientation (Fig. 1) in the first layers adsorbed on the plane surfaces of the clay minerals. The first water molecules are oriented because their configuration fits with that of the oxygen layers in the surface of the clay mineral units. The orientation tends to propagate itself through layers of water some molecules in thickness outward from the surfaces of the clay minerals. Starting with this concept of the structure of the adsorbed water, a satisfactory theory of the structure of soil materials in the plastic state can be evolved.

A mass or sheet of oriented water molecules would be rigid like ice rather than fluid, and therefore the initial adsorbed water would not be fluid. But as larger amounts of water are added to dry clay, the layers of oriented water molecules become thicker and thicker. Because the force orienting the water molecules is the structure of the surface of the clay minerals, it is not reasonable that oriented water would grow to an indefinite thickness on the clay mineral surfaces. Further the presence of adsorbed ions and molecules on the clay mineral surfaces would tend to restrict the growth of the oriented water. Therefore, at some distance from the clay mineral sur-

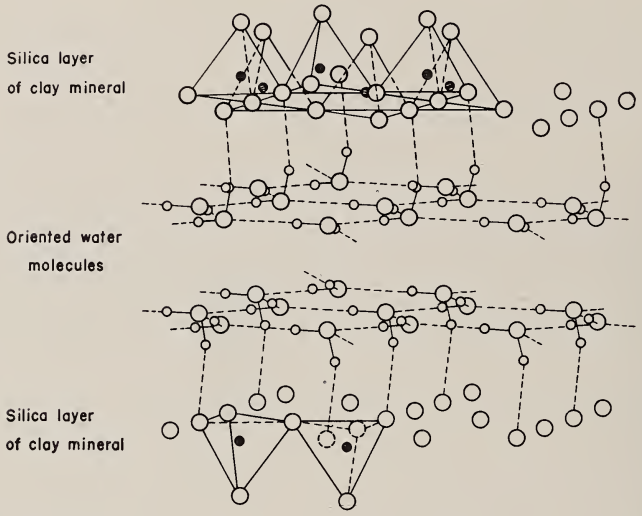


FIG. 1.—Schematic sketch of orientation of water molecules adsorbed on the basal surfaces of the clay minerals. Large circles represent oxygen atoms; small circles hydrogen atoms; small black or shaded circles silicon atoms (after Hendricks and Jefferson).

faces, the water molecules would not be oriented,* that is, they would be fluid.

Oriented water would develop from about all basal plane surfaces of the clay minerals, and the rigid adsorbed water of one surface would meet that of another surface. The rigid water would serve as a bond to hold the clay mineral units rigidly in place. With increasing amounts of water the adsorbed layers would become thicker until a thickness was reached at which orientation was nil or imperfect. Such water, having fluid properties, could act as a lubricant between the flakes. According to this concept, the plastic condition develops in a clay-water system when there is enough water to supply all the rigid water that can develop on available surfaces *and a little more water* that has poor or no orientation to act as a lubricant between flakes (Fig. 2). Large amounts of additional water provide much fluid water and give the system the properties of a fluid.

In soil materials, the transition from oriented to nonoriented water molecules (that is, from rigid to fluid water), may be abrupt or somewhat gradual, but usually it is rather abrupt. If this is true there should be a sharp break in the plastic properties at a given moisture content when increasing amounts of water are added to a dry soil material. Experimental data (Figs. 3, 4) show this. Figure 3 shows that there is an abrupt reduction in power required to extrude clay through a die when a certain moisture content is reached. Extrusion is exceedingly difficult until some fluid water is present. Curves that show compression strength of sand-clay-water mixtures (Fig. 4) show that maximum strength is developed within extremely narrow moisture limits which probably correspond to the maximum amount of rigid water that can be adsorbed. Additional amounts of adsorbed water are at least partially unoriented with attendant large decrease in compressive strength.

A time factor may be involved in the development of some plastic properties. For example, the compressive strength of some sand-clay-water mixtures increases gradually within short periods of time in compacted masses (Ref. 5). The explanation is that a certain amount of time is required for the water molecules to become oriented completely.

* A residual partial orientation of water, of course, exists in liquid water (Ref. 12).

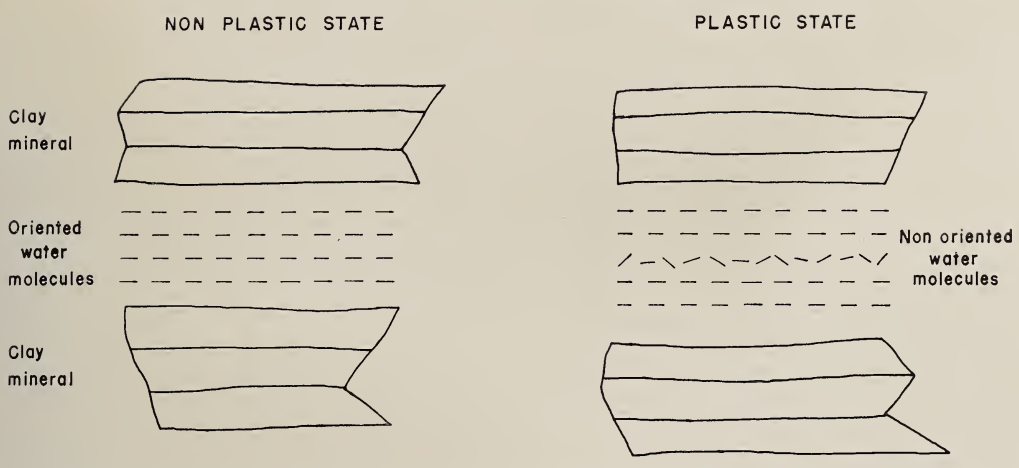


FIG. 2.—Schematic presentation of character of water in nonplastic and plastic states.

## EFFECT OF MINOR AMOUNTS OF CERTAIN COMPONENTS ON THE PROPERTIES OF SOIL-WATER SYSTEMS

Extremely small amounts of certain chemicals have a tremendous influence on the properties of soil materials. This has been known for some time but the explanation has been obscure. An example is the large change in viscosity of sodium montmorillonite-water slurries caused by the addition of traces of sodium hexametaphosphate (Ref. 13) (Table 1).

TABLE 1.—EFFECT OF $(NaPO_3)_6$ ON VISCOSITY OF SODIUM MONTMORILLONITE-WATER SUSPENSION

| | $(NaPO_3)_6$ percent | Viscosity in centipoises |
|---|---|---|
| Sodium montmorillonite.... | — | 48 |
| 8 percent water... | 0.2 | 23 |
| "slurry"..... | 0.4 | 18 |

Not all the components which can have such an effect are known, but in addition to phosphates small amounts of magnesium and boron are known to alter clay-bonding properties. Small amounts of sodium, hydrogen, and aluminum as exchangeable bases greatly alter certain plastic properties. Table 2 presents Atterberg Limits for natural clays (Ref. 14) and for some clays treated with various chemicals. The latter data are preliminary and were obtained in a detailed study underway in the writer's laboratory. The data show the tremendous effect of the $Na^+$ ion in montmorillonite clays as compared to that of $Ca^{++}$ or $H^+$, and the large effect of some chemicals on the "Limits" of Na-montmorillonite. The precise effect of the treating agents on illite and kaolinite remains to be determined, but the present data indicate that it is small. This is to be expected since the "Limits" for these natural clays are low and the exchange capacity for illite and kaolinite are also low (20-40 and 3-15 respectively).

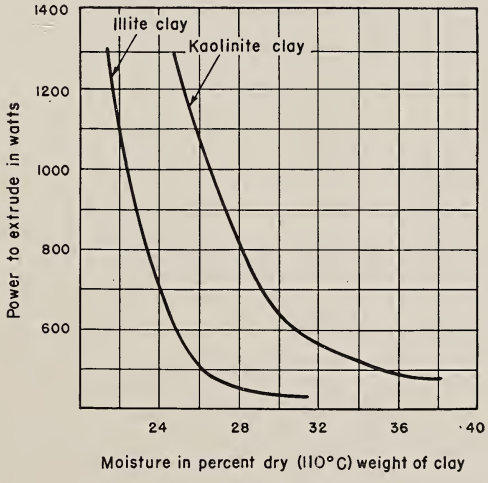


FIG. 3.—Relation of tempering water in clay and the power necessary to extrude clays through an auger machine.

TABLE 2.—ATTERBERG LIMITS

| MATERIALS STUDIED | PLASTIC LIMIT | | | | LIQUID LIMIT | | | | PLASTIC INDEX | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Untreated | $H_3PO_4$* | $H_2SO_4$* | $Na_6(PO_3)_6$* | Untreated | $H_3PO_4$ | $H_2SO_4$ | $Na_6(PO_3)_6$ | Untreated | $H_3PO_4$ | $H_2SO_4$ | $Na_6(PO_3)_6$ |
| *Montmorillonite* | | | | | | | | | | | | |
| 1. $Na^+$ exchangeable base. Wyoming | 97 | 54 | 50 | 48 | 700 | 340 | 250 | 395 | 603 | 286 | 200 | 347 |
| 2. $Ca^{++}$ exchangeable base. Arizona | 72 | 63 | 77 | | 124 | 119 | 142 | | 52 | 56 | 65 | |
| 3. $Ca^{++}H^+$ exchangeable base. Mississippi | 82 | | | | 118 | | | | 36 | | | |
| *Illite* | | | | | | | | | | | | |
| 4. LaSalle County, Ill. | 25 | 23 | 26 | 21 | 36 | 35 | 36 | 31 | 11 | 12 | 10 | 10 |
| 5. Vermilion County, Ill. | 24 | | | | 29 | | | | 5 | | | |
| *Kaolinite* | | | | | | | | | | | | |
| 6. Georgia | 30 | | | | 35 | | | | 5 | | | |
| 7. Union County, Ill. | 37 | 35 | 32 | | 58 | 68 | 68 | | 21 | 33 | 36 | |
| *Natural mixtures* | | | | | | | | | | | | |
| 8. Illite plus 10% montmorillonite. Greene County, Ill. | 26 | 27 | 28 | 25 | 58 | 52 | 61 | 48 | 32 | 25 | 33 | 23 |
| 9. Illite plus 5% montmorillonite. Grundy County, Ill. | 36 | 34 | 35 | | 61 | 61 | 62 | | 25 | 27 | 27 | |
| 10. Kaolinite plus 10% montmorillonite. Georgia | 33 | 31 | 31 | 39 | 65 | 65 | 74 | 67 | 32 | 34 | 43 | 23 |

* Chemical added to tempering water in such quantity that the acid radical equalled the base-exchange capacity.

A satisfactory explanation for the action of most of these components is that they influence the orientation of the adsorbed water molecules. The influence may be in the perfection of the orientation, the thickness to which good orientation can develop, or the abruptness of the transition from oriented to nonoriented water.

In the case of phosphates, the configuration of the phosphate unit (Ref. 1) is such that it would about fit into the configuration of the water molecules. The phosphate itself tends to leave a donor surface so that any water associated with it would not tend to fit into the oriented water associated with the clay surfaces. The result would be to disrupt the orientation of the water molecules without completely destroying it and thereby to increase the fluidity of the water between flakes which in turn would reduce viscosity.

In the case of small amounts of exchangeable sodium, for some reason not completely understood, the exchangeable $Na^+$ favors the development of thick layers of oriented water with gradual transition to nonoriented water. In sodium montmorillonites good orientation may extend through at least 100 molecular layers. When cal-

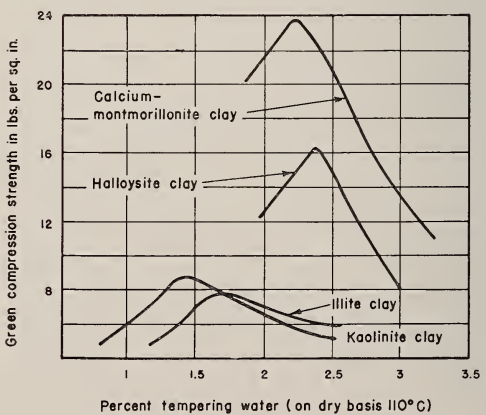


FIG. 4.—Relation of compression strength to tempering water and sand-clay mixtures containing 6 percent clay.

cium is the exchangeable ion the oriented water hull is very thin (a few molecular layers) and the transition to nonoriented water molecules is abrupt (Ref. 5). Calcium is the most frequent exchangeable base in soil materials, hence an abrupt transition of character of adsorbed water and resulting properties is usually encountered.

The application of the foregoing to engineering problems is clear. If one is dealing with a soil material with a moisture content about equal to that which can be held in a rigid form, any change in either amount of water or in chemical component might cause a tremendous effect on the properties of the soil. In general terms, it appears that soil materials and their environments are in equilibrium, but even slight changes may destroy the balance, causing great changes of properties. For instance, equilibrium would be destroyed by changes in amount or movement of groundwater, and by changes in the amount of adsorbed $Ca^{++}$ that would follow construction using Portland cement in a soil material originally containing $Na^{+}$. The possibility of tremendous effects on the properties of soil materials adjacent to concrete structures because of base-exchange calcium provided by the concrete itself appears to have been overlooked.

## Influence of Clay Minerals

The plastic properties of soil materials are largely determined by the kind of clay minerals that compose them (Ref. 3), and White (Ref. 14) has recently carefully measured the Atterberg Limits of pure clay-mineral samples (Table 2). The Atterberg Limits of kaolinite and illite are roughly the same. Sample 7 is relatively finer grained than sample 6, indicating the order of magnitude of the increase in the "Limits," particularly the Liquid Limit, as the particle size of kaolinite or illite decreases.

The Plastic Limit for montmorillonite is about three times that of kaolinite or illite. The Liquid Limit for montmorillonites carrying $Ca^{++}$ and/or $H^{+}$ is about three to four times that of the other clay minerals, whereas that of $Na^{+}$ montmorillonite is five to six times that of the $Ca^{++}$ or $H^{+}$ montmorillonite and as much as twenty times that of kaolinite or illite. Clearly montmorillonite is the component, particularly when $Na^{+}$ is present, with the tremendous plastic properties.

Samples 8 and 9 (Table 2) contain 5 to 10 percent montmorillonite in addition to illite. Sample 10 contains 10 percent montmorillonite in addition to kaolinite. The presence of montmorillonite causes little change in the Plastic Limit, but increases the Liquid Limit about twofold so that the Plastic Index is increased four to six times by only 5 percent montmorillonite.

Montmorillonite has a peculiar lattice structure (Ref. 9) which permits water to penetrate between the individual unit layers about 9.5°A thick, thereby separating them. The separation can be substantially complete in the presence of considerable amounts of water, particularly when sodium is the exchangeable base. Both basal plane surfaces of the montmorillonite units are composed of oxygens so arranged as to foster the growth of oriented water molecules. In addition montmorillonite has high base-exchange capacity (about 100 milliequivalents per 100 grams) so that montmorillonite surfaces are apt to carry adsorbed ions that favor the adsorption of water. The high plastic properties of soil materials composed of montmorillonite are due to its property of breaking down into exceedingly small flake-shape units with a consequent tremendous surface with particular ability to adsorb water.

Where soil materials are composed of a mixture of montmorillonite and other clay minerals, the components may be present either as mixtures of discrete aggregate particles of the individual clay minerals or as very intimate interlayerings of one or a few unit layers of montmorillonite with several unit layers of the other clay minerals. In the former case the effect on properties is about proportional to the amount of montmorillonite present. In the latter case, the effect is much greater as shown in Table 2. The explanation is as follows: Illite and kaolinite occur in soil

materials in aggregate particles which do not come apart into much smaller units in the presence of water. If, however, layers of montmorillonite are interspersed through the kaolinite or illite aggregates, the montmorillonite forms planes of weakness along which the aggregates can break up in the presence of water. Obviously, under such conditions, relatively few such planes would cause relatively great breaking up of the clay mineral particles with attendant great increase in plastic properties.

## Organic Material in Soils

Organic material can be present in soils in two forms: (a) as discrete particles such as fragments of wood, bits of leaves, and spores, and (b) as exceedingly fine material that is in the colloidal or molecular state.

It has long been known that organic material, particularly in the colloidal form, can increase the plastic properties of clay. The exact nature of the organic material in soils is still not known, but recent work in several laboratories has provided basic data on the adsorption of organic molecules by the clay minerals. The findings go a long way in explaining the manner in which organic material is present in soils and its influence on soil properties.

Gieseking (Ref. 2) and later Hendricks (Ref. 8) showed that some organic molecules were adsorbed on the basal plane surfaces of the montmorillonite clay mineral units, that is on the same surfaces that adsorb water. MacEwan (Ref. 11), investigating the kind of organics adsorbed, has shown that those with polar groups are favored and that both montmorillonite and halloysite may adsorb organics between the unit cells. Grim, Allaway, and Cuthbert (Ref. 6) have shown that the clay minerals illite and kaolinite also have some adsorption capacity for organics.

Since the organic molecules are adsorbed on the same surfaces that can adsorb water, a decrease or elimination of water adsorbing capacity would be an expected result of the adsorption of organics. This has been found to be true (Refs. 6, 8) and is one of the effects on soil properties of the adsorbed organics.

Jordan (Ref. 10) has recently shown that certain clay minerals, notably montmorillonite, when carrying adsorbed organic molecules of particular kinds are organophilic toward other organics. Such clay mineral-organic complexes do not swell in water, but they do swell tremendously in the presence of suitable organic liquids forming gels. Such gels are very stable, show almost no air-drying, and have very low bearing power. Organic-clay mineral complexes are undoubtedly to be found in nature. Swamps, bogs, and slough fillings would be probable places, and soils containing them would have striking and unusual properties.

## Summary and Conclusions

A theory of the structure of soil materials in the plastic state is presented that is based on the oriented configuration of the water molecules initially adsorbed by the clay mineral components of such materials. It is shown that the plastic properties, particularly the Atterberg Limits, may vary greatly because of the presence of small amounts of certain chemical components, and an explanation is offered based on the effect of such components on the orientation of the water molecules.

It is shown that relatively small amounts of montmorillonite may cause a relatively great increase in the plastic properties of soil materials. The structure of montmorillonite is such that when it is interlayered with other clay minerals, it forms planes of weakness that permit relatively great break-down of the clay mineral particles with attendant great increases in plasticity.

Certain kinds of organic molecules and some clay mineral may form gels. Such components probably explain the unusual and extreme properties in some peculiar soil materials.

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# THE COMPOSITION IN RELATION TO THE PROPERTIES OF CERTAIN SOILS

BY

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## Introduction

Investigations are in progress in the laboratories of the Illinois State Geological Survey, Urbana, Illinois, studying the specific relations between the factors of composition (Ref. 2)* of soil materials and their soil mechanics properties. The problem is being approached in two ways: first, by the determination of the properties of pure clay minerals, of controlled mixtures of pure clay minerals and nonclay minerals, and of pure clay minerals prepared with specific adsorbed ions; and second, by making complete analyses of the composition and texture of a series of soils known by experience and tests to have unusual properties, in an effort to locate the cause of the unusual character. These soils are being obtained through the help of Professor Terzaghi of Harvard University and Professor Peck of the University of Illinois, whose cooperation is gratefully acknowledged.

This paper presents briefly the methods used in the analysis of the soils, the composition of nine soils of widely different composition, and a discussion of the relation between composition and properties of the individual soils. The soils considered herein have been selected from a large number that have been analyzed because they illustrate some broad general relationships between composition and properties.

## Method of Analysis

Only about half of the samples were received sealed in paraffin, so that natural moisture content could not be determined for all samples. Particle size distribution analyses were made by the pipette method, using sodium hexametaphosphate as the dispersing agent. The mineral composition of the coarser sized fractions obtained in the pipette analysis was determined by the petrographic microscope. In addition, an effort was made to separate, by repeated sedimentation, all of the minus 2 micron and minus 1 micron fractions without the use of any dispersing agents. The composition of these fine fractions was determined by X-ray diffraction and differential thermal methods. Base-exchange capacity, pH, exchangeable bases, and soluble salts were determined for each soil by the conventional methods used by soil scientists in agriculture. Ammonium acetate was the leaching agent used in the determination of the exchangeable bases and soluble salts.

Particle size distribution curves for all but one of the soils are shown in figures 1 to 8 in the form of cumulative curves, and by frequency distribution curves constructed by the graphic differentiation method described by Krumbein (Ref. 7). It will be found that some of the frequency curves have been slightly smoothed. This was done in order to eliminate minor irregularities which are not significant and which are probably outside of the limit of error of the particle size data. The frequency curves show the relative abundance of various size grades by the area under the curve. For example, the percentage of material between 0.005 and 0.002 mm. in any sample is obtained by dividing that portion of the area under the curve which is bounded by vertical lines constructed at the 0.005 and 0.002 mm. divisions of the horizontal axis by the total area under the entire curve.

The particle size distribution of each of the component minerals of those samples that could be satisfactorily dispersed is shown also in the form of frequency distribution curves. The relative abundance of the component minerals in any given particle

* References are given at end of paper, p. 21.

TABLE 1.—ANALYTICAL DATA

| Sample Number | Location | Percent minus 1 micron | pH | Base-exchange capacity | Exchangeable bases and soluble salts in me/100 grams | Clay mineral composition | Liquid limit | Natural moisture content | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| 1. | Brown Cairo, Egypt | 38.7 | 8.0 | 45.1 | 3.5 $K^+$<br>28.5 $Na^+$<br>26.0 $Ca^{++}$<br>29.0 $Mg^{++}$ | Largely montmorillonite, poorly crystallized | 60–80* | 25–40* | Swells intensely |
| 2. | Dark Cairo, Egypt | 56.5 | 7.6 | 50.6 | .6 $K^+$<br>2.30 $Na^+$<br>38.4 $Ca^{++}$<br>17.85 $Mg^{++}$ | Largely montmorillonite, poorly crystallized | 40–50* | 30–50* | Swelling inconsequential |
| 3. | Alexandria, Egypt | 68.0 | 7.9 | 51.2 | 5.0 $K^+$<br>228.0 $Na^+$<br>14.27 $Ca^{++}$<br>26.73 $Mg^{++}$ | Largely montmorillonite, poorly crystallized | 100±* | 100+* | High compressibility |
| 4. | Helouan, Egypt | 20.0 | 8.4 | 53.9 | 1.34 $K^+$<br>57.22 $Na^+$<br>54.5 $Ca^{++}$<br>16.7 $Mg^{++}$ | Largely montmorillonite, poorly crystalline | | | Swells greatly |
| 5. | "Kurzawka" soil, Poland | 7.2 | 8.8 | 5 | .36 $K^+$<br>1.7 $Na^+$<br>21.88 $Ca^{++}$<br>0 $Mg^{++}$ | Largely halloysite and allophane | | | |
| 6. | Cucaracha clay Gaillard cut Panama Canal, Panama | 19.9 | 9.1 | 68.4 | .78 $K^+$<br>3.21 $Na^+$<br>63.95 $Ca^{++}$<br>15.67 $Mg^{++}$ | Montmorillonite type dominant, also some halloysite | 37 | 16.47 | |
| 7. | Nespelm silt Coulee Dam, Washington, U.S.A. | 11.3 | 8.1 | 6 | .24 $K^+$<br>1.42 $Na^+$<br>18.35 $Ca^{++}$<br>28.5 $Mg^{++}$ | Illite | 44.5 | | |
| 8. | Nespelm silt Coulee Dam Washington, U.S.A. | 54.5 | 8.1 | 17.9 | .48 $K^+$<br>1.25 $Na^+$<br>17.18 $Ca^{++}$<br>4.14 $Mg^{++}$ | Illite with small amounts kaolinite and montmorillonite | 59.15 | 4.75 | |
| 9. | London clay Chinford Reservoir, London | 46.1 | 6.0 | 24.7 | 0.5 $K^+$<br>1.3 $Na^+$<br>22.4 $Ca^{++}$<br>.3 $Mg^{++}$<br>9.7 $SO_4$ | Illite with small amounts of kaolinite and montmorillonite | 60–75† | 22–28† | |

* Personal communication from Prof. K. Terzaghi.
† See Ref. 1.

size can be obtained from the relative areas under the frequency distribution curves designated for the particular minerals.

Liquid Limit determinations were obtained for all the samples for which an adequate quantity of sample was available.

## RESULTS OF ANALYSES

The results of the analyses are given in figures 1 to 8 and Table 1.

## Discussion

*Soils 1 and 2, Cairo, Egypt* (figs. 1 and 2). Professor Terzaghi* contributes the following regarding these soils: "Soils 1 and 2 are from a test boring in the central part of Cairo, Egypt, east of the east bank of the river Nile and are typical for Cairo clays. Total thickness of both clay deposits combined is about 30 feet. The surface of the clay stratum is covered with a thin layer of artificial fill. The clay rests on a very thick stratum of fine sand which becomes coarser with depth. The brown clay constitutes the top and the dark one the bottom layer. The liquid limit of the brown (upper) clay varies between 60 and 80 percent and the natural water content between 25 and 40. The liquid limit of the dark (lower) clay varies between 40 and 50 and the natural water content between 30 and 50. The upper clay is stiff or very stiff and the lower one soft to medium. The upper clay swells intensely whereas the swelling of the lower one is inconsequential."

The dominant composition factor in soils 1 and 2 is the presence of montmorillonite as the clay mineral component which would account for the Liquid Limit values, the high natural water contents, and the swelling characteristics. The montmorillonite clay mineral is unique in that water enters between the individual unit cell layers (Ref. 3), thereby causing the lattice to expand and the mineral to swell; this is accompanied by great water adsorbing and holding capacity. Further, the concept of the orientation of the adsorbed water molecules (Ref. 2), as applied to soil properties, and the consequent rigidity of the water in the first few molecular layers accounts for the solid character of these soils at relatively high water contents.

Montmorillonite has high base-exchange capacity and, as a consequence, soils 1 and 2 have relatively high base-exchange capacity. The clay-water relationship of montmorillonite depends greatly on the character of the exchangeable base carried by the mineral, and variations in exchangeable base

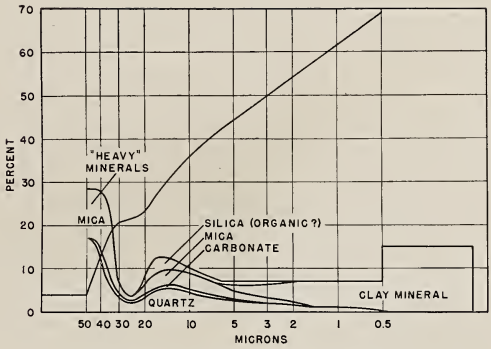


Fig. 1.—Brown clay, Cairo.

composition explain the difference in the properties of these two soils. Thus when sodium is the exchangeable base, water can enter readily between the unit cell layers so that thick adsorbed water layers develop. If calcium or magnesium is the exchangeable base, considerably thinner adsorbed water layers develop. Sodium montmorillonite clays tend to swell very much, whereas calcium or magnesium montmorillonite clays tend to swell very little. Soil 1, which swells, carries sodium as the predominant exchangeable base; whereas soil 2, which does not swell appreciably, probably has no significant exchangeable sodium. The sodium clay would be expected also to have a higher Liquid Limit than the calcium clay.

Of considerable importance is the point that not all of the base-exchange capacity need be satisfied with sodium in order to produce the clay-water relationship characteristic of this cation. Generally when only a relatively small percentage of the exchange capacity is composed of sodium, pronounced swelling and water-adsorbing

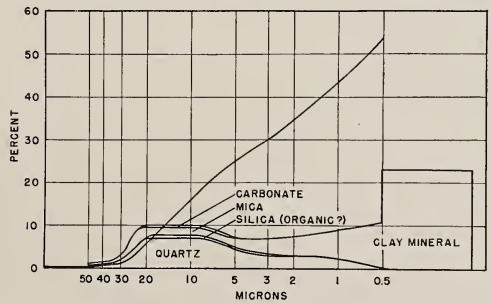


Fig. 2.—Dark clay, Cairo.

* Personal communication.

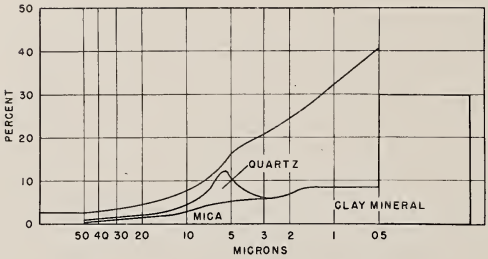


FIG. 3.—Soft clay, near Alexandria.

properties are characteristic of montmorillonite clay.

The foregoing characteristics of sodium versus calcium (and magnesium) montmorillonite clays apply only when the clay is exposed to an excess of water. In the presence of limited amounts of moisture, that is, moisture adequate to form adsorbed water layers only a few molecular layers thick (yielding adsorbed water values up to about 60 percent), calcium montmorillonite comes to equilibrium at higher moisture content than sodium montmorillonite (Ref. 8). Thus calcium montmorillonite has been used successfully commercially as a dessicant, whereas sodium montmorillonite is unsatisfactory for this purpose. Therefore the higher natural moisture content of soil 2, which swells very little and has the lower Liquid Limit, is in accord with the presence of calcium or possibly magnesium as the exchangeable ion.

It follows from the high base-exchange capacity of montmorillonite and the different properties that result from difference in the exchangeable bases, that any change in the base-exchange composition of such a soil as 1 and 2 would cause a decided change in properties. A change in groundwater movement or a change in the character of the salts dissolved in the groundwater would cause the soil to change its properties. For example, placing concrete structures in such a soil might well provide a supply of $Ca^{++}$ to the water moving through the soil, thus causing a base-exchange reaction.

Another characteristic worth noting for montmorillonite is that the minerals readily adsorb water again after drying *unless all* of the adsorbed water has been removed. The adsorbed water may be lost at temperatures somewhat below 100°C., but drying at such low temperatures is relatively slow. Therefore, samples of such soils as 1 and 2 which had been dried thoroughly would probably not regain their properties, even approximately, after wetting again.

There seems to be nothing in the particle size distribution or other determined properties of these soils that would exert an important influence on their properties.

*Soil 3, Alexandria, Egypt* (fig. 3). According to Professor Terzaghi* this soil "comes from a boring from the southern boundaries of Alexandria. The stratum of soft clay has a thickness of about 40 feet and rests on a thick sand stratum. The water content of this clay is commonly about 100, the Liquid Limit is also close to 100, and the clay is very compressible. As a consequence catastrophic settlements have occurred. The high compressibility of this clay appears to be due to a high organic content."

As in soils 1 and 2, the properties of this soil are to a great extent a consequence of the presence of montmorillonite and also of the presence of sodium in large quantities, both as an exchangeable base and as a readily soluble salt. In addition, this soil contains a high percentage of very fine clay (68 percent less than 1 micron and 59 percent less than 0.5 micron) which would further add to its plastic properties.

The soil has a high organic content (sample was too small for quantitative determination) which could well be responsible for much of its compressibility. The clay minerals montmorillonite and halloysite have the property of adsorbing certain organic molecules and then of forming stiff gel-like masses in the presence of other organic compounds (Ref. 6). Such masses would be expected to have little strength. It is likely that the presence of such masses in montmorillonite and halloysite soils of relatively high organic content are an important factor in determining the properties of such soils.

The particle size distribution of the quartz, which is the dominant nonclay mineral component, shows a concentration

* Personal communication.

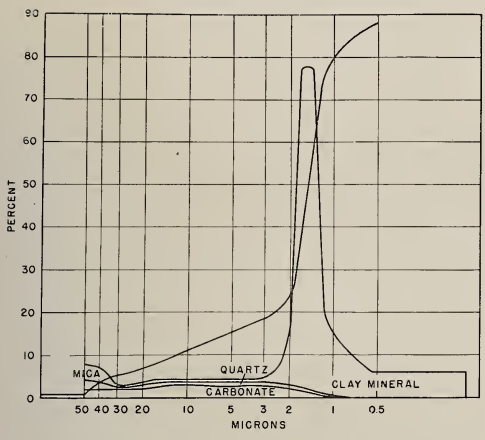


FIG. 4.—Clay at Helouan, Egypt.

in the fine silt range at about 5-6 microns. Such a concentration of a silt size could add to the peculiar properties that have been noted for this soil.

*Soil 4, Helouan, Egypt* (fig. 4). According to Professor Terzaghi* this sample "was taken from a shallow sewer trench in Helouan about 50 km. south of Cairo at the foot of the east slope of the mountains which separate the Nile Valley from Suez. The clay was very stiff. As a result of the failure of a water conduit beneath the floor of a nearby factory building, the floor rose more than a foot."

The presence of montmorillonite as the clay mineral component and the abundance of $Na^+$ would adequately account for the high swelling of the soil.

The particle size distribution of this soil, with about 75 percent finer than 2 microns and about 55 percent in the 2 to 1 micron size grade, is undoubtedly very significant in determining the properties of the material. The analytical data show that at least a considerable part of this coarse clay is montmorillonite. The author has studied soils of somewhat similar composition and found that almost any particle size distribution can be obtained by varying the dispersing procedure, for example, the amount of stirring in a mechanical mixer, and the dispersing agent. The reason is that the 2 to 1 micron particles are aggregates or book-like particles of clay minerals which come apart to varying degrees, depending on the working of the material. The break-down of the aggregates or book-like masses is particularly easy when montmorillonite is present because it forms planes of weakness. Unfortunately only a small amount of Helouan soil was available for testing and specific dispersion data could not be obtained.

In general, soils with the foregoing composition yield particle size distribution data of little significance. Further, it might be difficult to evaluate test data for such soils because their properties would undoubtedly be very sensitive to any working or disturbing, or to any environmental change such as fluctuation in moisture content, ion content of groundwater, etc., which would either split the coarse clay particles or vary the ease with which they separate.

*Soil 5, "Kurzawka" soil, Poland* (fig. 5). A small dried sample of this soil was received from Ir. A. Pogány of Krakow, Poland. It is not possible to correlate this sample with the "Kurzawka" samples recently described by Pogány (Ref. 9) and it is not known how typical the sample is of the general characteristics of the Kurzawka. Because the sample received was small and was dry it was impossible to determine its particular properties. However, the sample does have a noteworthy composition which illustrates some generalities in the relation between clay mineral

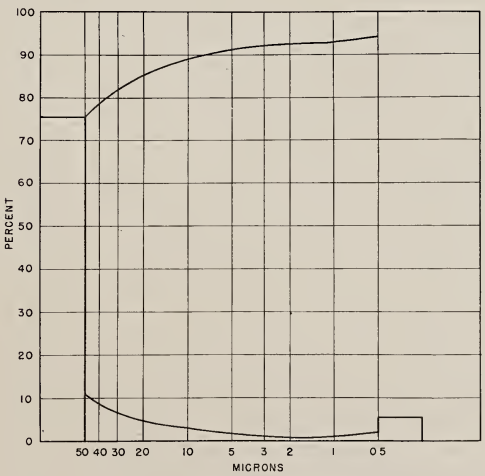


FIG. 5.—"Kurzawka" soil, Poland.

* Personal communication.

composition and properties, and for that reason it is considered herein.

The material is composed of halloysite and allophane and consequently has low base-exchange capacity (Ref. 3) and should not swell. A microscopic examination of the individual size grade fractions, obtained on making the particle size analyses (Fig. 5), indicates that each grade is composed of aggregates of silt-sized nonclay minerals bonded together by the clay minerals. The particle size analysis, therefore, does not show the size grade distribution of the individual component minerals. Halloysite and allophane, unlike some other clay minerals such as the montmorillonites, are not broken up readily when they are worked or agitated in water. The aggregates in this Kurzawka soil, therefore, are likely to be resistant to working, and the particle size distribution might well represent the material as it actually exists in natural condition.

The halloysite clay minerals have certain unique properties which would be carried over to soils containing them. There are two forms of halloysite, a higher hydrate form with $4H_2O$ in its composition, and a lower hydrate form with $2H_2O$. A transition which is not ordinarily reversible from the higher to lower form takes place rapidly at temperatures of about 60°C. and slowly at lower temperatures. Halloysite materials, as found in their natural condition, are frequently in a transition state between the $4H_2O$ and $2H_2O$ form. Material in the transition state frequently has very high plastic properties (Ref. 4), whereas material in either the low or high hydrate form is relatively nonplastic. It follows from the foregoing consideration of halloysite properties, that any drying of a soil containing this clay mineral would cause a great change in properties. Great care would be needed to preserve the moisture content in samples selected for testing, and one could not generally expect to use the same sample for repeated check tests. Of greater significance is the fact that working a halloysite soil during construction might be expected to permit some drying, with consequent great change in properties. In general, drying of any soil causes some change in properties, but in halloysite soils there is apt to be a different kind of phenomenon. For example, a slight loss of water from a soil composed of halloysite in highly hydrated form would tend to develop a plastic from an unplastic soil.

Halloysite materials also have the property of developing "air-set" strength (Ref. 5). If the compressive strength of a test specimen formed from a material containing intermediate halloysite is determined immediately after forming and again some hours or days after forming (with the sample retained under conditions in which no moisture is lost), it will be found that the material has gained in strength without a correlative loss of water. The explanation for this "air-set" strength appears to be that the water present in such a soil mass gradually and slowly develops an orientation net on the surfaces of the halloysite, along with which there is an increase in strength.

Halloysite (like montmorillonite but unlike most of the other clay minerals) adsorbs certain organic compounds, and therefore halloysite soils that have an appreciable organic content may contain organic halloysite gels of considerable instability.

*Soil 6, Cucaracha clay, Gaillard cut, Panama Canal, Panama.* Several samples of this clay were received from Col. James H. Stratton, U. S. Army Engineers.

The particle size analysis of this material is not significant and consequently no size distribution curve is presented. The material as received is a solid rock containing an enormous number of slickensided fracture surfaces. The particle size analysis obtained is the result of the procedure used in preparing the sample for analysis, i.e., slaking time, dispersing agent used, crushing of sample, and has, therefore, no inherent meaning so far as properties of the clay is concerned.

The dominant clay mineral component is montmorillonite with also a considerable amount of halloysite. The high base-exchange capacity reflects the montmorillonite, and the ion determinations (Table 1) show that calcium is the dominant exchange-

able base. Because calcium, rather than sodium, is the dominant base, the montmorillonite would not be of the high swelling variety.

Clay materials containing montmorillonite tend to break down readily in water to very small particle sizes. The Cucaracha clay is unique in being a montmorillonite material which does not so break down. It also has a much lower liquid limit and natural moisture content than is usual for montmorillonite clays (Ref. 2). There are three reasons for this unique character and undoubtedly they are all significant. First, as noted above, the montmorillonite carries calcium as the exchangeable base; and calcium montmorillonite clays, unlike those carrying $Na^+$, are not so readily dispersible. Second, the presence of halloysite would retard dispersion of particles. The study of a considerable number of soils has shown that those containing halloysite generally are difficult or impossible to disperse into their constituent minerals or into any significant reproducible particle size distribution. Third, the Cucaracha clay has been subject to high earth pressures, as evidenced by the slickenside surfaces and the presence of faults* in the geologic section. This pressure would tend to force the individual montmorillonite units close together, and in many instances probably completely collapse the structure, forcing all the water out from between the layers. As noted above, when this happens water goes back into the structure with great difficulty, and such material does not have the usual properties of montmorillonite.

The two factors that are probably dominant in controlling the characteristics of the Cucaracha clay are: first, the slickensided surfaces that provide a tremendous number of planes of weakness along which water could penetrate, giving the material then little strength, and second, the collapsed montmorillonite. In the case of collapsed montmorillonite some water would no doubt enter very slowly between the unit layers in any masses of clay where water was available in considerable abundance with a consequent change in properties of the clay. The slickensided fracture surfaces influence properties not only because they provide planes of weakness but also because they provide means of access of water to the montmorillonite.

*Soil 7, Nespelm Silt, Bank of Reservoir, upstream from Coulee Dam, Columbia River, Washington, U.S.A.* (fig. 6). The particle size distribution, with the high concentration in the very fine silt range, is undoubtedly the factor determining the properties of this material. Possibly the relatively high concentration of mica in the very fine silt is significant also. The clay mineral illite should cause no unusual properties.

Engineers have long known that such silts have properties, particularly extreme instability when water saturated, that make them difficult or even dangerous to use. The explanation probably lies in the character of the bond between the silt particles. At low moisture contents the bond is probably a thin molecular film of water which has rigidity and bonding strength because of the orientation of the water molecules. Additional water would thicken the water layer, with a consequent loss in rigidity and bond between particles. The cause of the orientation of the water molecules probably in part resides in the internal structure of the silt particles, and therefore would be expected to decrease with increasing distance from the surface of the

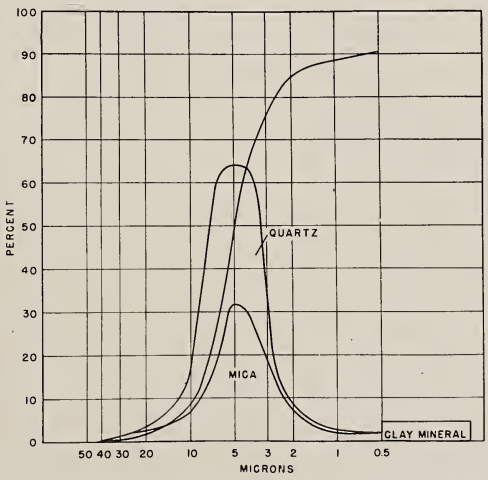


FIG. 6.—Nespelm silt, Columbia River upstream of Coulee Dam.

* Personal communication, J. H. Stratton.

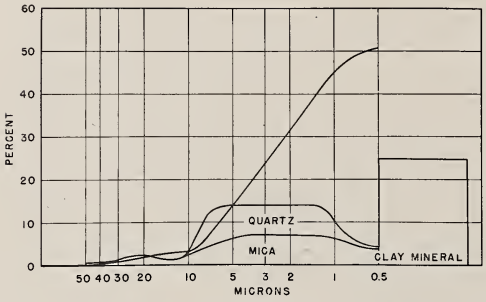


FIG. 7.—Nespelm silt, Columbia River, Kettle Falls area.

silt particles. It would probably operate through distances of only a few molecular layers of water. It seems likely that the cations present in this silt would also influence the orientation of the water molecules. By analogy with the adsorbed water of clays, certain ions such as $Ca^{++}$ would probably cause a thicker film of highly rigid water than other ions such as $Na^{+}$. If this is true, a change in the character of the ion present would affect the stability of the soil without necessarily any change in the water content. For example, the placing of a mass of concrete in such a soil thereby flooding it with calcium ions might well change its stability without any change in its water content.

*Soil 8, Nespelm Silt, Kettle Falls area, west bank of Columbia River, Coulee Dam area, Washington, U.S.A.* (fig. 7). This sample, like soil 7 from the same area, is also characterized by a size grade distribution showing a concentration in the fine silt size. The sample, however, contains considerably more clay (54.4 percent as compared to 11.3 percent of minus one micron material for soil 7) and the clay contains some montmorillonite. An increase in abundance of illite clay accompanied by a relative decrease in the concentration of silt sized material would be expected to increase the stability of the material, perhaps by providing a clay bond which would be stronger than a water bond between the silt particles. However, the presence of montmorillonite, even in small amounts, along with the illite would reduce the stability derived from the increased clay content.

The higher Liquid Limits and higher base-exchange capacity of this silt as compared to sample 7 are, of course, a consequence of the increased clay content and the presence of montmorillonite.

*Soil 9, London clay, Chinford Reservoir Puddle Clay, London* (fig. 8). This sample was kindly sent by Prof. A. W. Skempton of the Imperial College of Science and Technology, London.

The clay mineral component of this London clay sample is about 70 percent illite, 20 percent kaolinite, and 10 percent montmorillonite. In general, the illite and kaolinite should not yield a material with difficult properties. As much as 10 percent montmorillonite in a soil would have distinct influence on properties and would account for the high shrinkage (Ref. 10) and generally high plastic properties. A fairly high content of clay sized material (46.1 percent minus 1 micron) would favor also high plastic properties. A relatively small amount of montmorillonite tends to influence soil properties to a relatively large degree because it provides planes of weakness throughout the material.

The sample studied was acid with a pH of 6. The determinations of the easily soluble salts indicate too few cations to satisfy the exchange capacity after assignment of enough cations to satisfy the $SO_4$ − −, thereby indicating that the exchange positions on the clay are occupied chiefly by $H^{+}$ as well as $Ca^{++}$. As $Ca^{++}$ and $H^{+}$ are the exchangeable ions in this sample, it should show insignificant swelling.

The clay has a moderate base-exchange capacity. The presence of some montmoril-

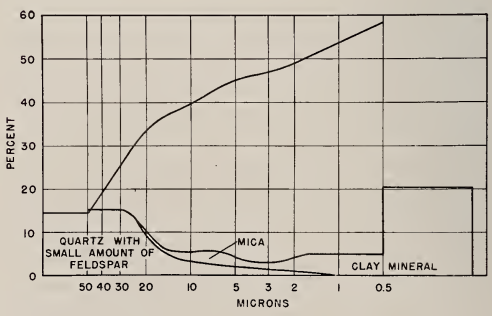


FIG. 8.—London clay, Chinford Reservoir.

lonite makes it higher than would be the case for either illite or kaolinite alone. There is no great likelihood of a base-exchange reaction causing a change in properties of such a clay because $Ca^{++}$ and particularly $H^{+}$ are relatively more resistant to exchange than many other common ions (e.g. $Na^{+}$).

In clays of this kind frequently the pH increases from the surface downward, with upper clays being acid and lower clays being alkaline. In the weathering process downward seeping waters tend to remove alkalies and alkaline earths progressively from the surface downward. There should, of course, be a correlative change in properties of the clay and in sensitivity to base-exchange reactions.

## Composition Factors of Particular Significance in Controlling Soil Properties

The analyses of these soils and of others that have somewhat unusual properties permit a listing of certain factors of composition that are apt to give a soil unusual properties. It must be emphasized that the study of additional soils will undoubtedly add additional factors, and also that there will be some soils in which these factors do not produce particularly bad soil properties because other factors tend to neutralize them. It is noteworthy that these factors of composition are such as to make it difficult to predict, on the basis of laboratory tests, the behavior of a soil in the ground under load and throughout a future interval of time. Also they cause a soil to have properties that are quite likely to change as a consequence of changes in soil environment, such as changes in groundwater circulation or changes due to construction. The factors are as follows:

a) Clay mineral composition containing montmorillonite minerals.

b) Clay mineral composition containing halloysite minerals.

c) High base-exchange capacity.

d) Sodium as an important exchangeable base.

e) High soluble salt content.

f) Concentration of component particles in fine silt size grade.

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